DEFICIENCY OF 'THIN' STELLAR BARS IN SEYFERT HOST GALAXIES

Isaac Shlosman[1]

Reynier F. Peletier[2]

Johan H. Knapen[3,4]

[1] *Department of Physics & Astronomy, University of Kentucky, Lexington, KY 40506-0055, USA, E-mail:* shlosman@pa.uky.edu

[2] *School of Physics and Astronomy, University of Nottingham, University Park, Nottingham, NG7 2RD, UK, E-mail:* reynier.peletier@nottingham.ac.uk

[3] *Isaac Newton Group of Telescopes, Apartado 321, Santa Cruz de La Palma, E-38700 Spain*

[4] *On leave from Department of Physical Sciences, University of Hertfordshire, Hatfield, Herts AL10 9AB, UK, E-mail:* knapen@star.herts.ac.uk

ABSTRACT

Using all available major samples of Seyfert galaxies and their corresponding control samples of closely matched non-active galaxies, we find that the bar ellipticities (or axial ratios) in Seyfert galaxies are systematically different from those in non-active galaxies. Overall, there is a deficiency of bars with large ellipticities (i.e., 'fat' or 'weak' bars) in Seyferts, compared to non-active galaxies. Accompanied with a large dispersion due to small number statistics, this effect is strictly speaking at the 2σ level.

To obtain this result, the active galaxy samples of near-infrared surface photometry were matched to those of normal galaxies in type, host galaxy ellipticity, absolute magnitude, and, to some extent, in redshift. We discuss possible theoretical explanations of this phenomenon within the framework of galactic evolution, and, in particular, of radial gas redistribution in barred galaxies. Our conclusions provide further evidence that Seyfert hosts differ systematically from their non-active counterparts on scales of a few kpc.

Subject headings: Galaxies: Evolution — Galaxies: Nuclei — Galaxies: Seyfert — Galaxies: Spiral — Galaxies: Statistics — Infrared: Galaxies

1. Introduction

The relationship between the large-scale morphology of Seyfert (Sy) host galaxies and the central non-stellar activity is a long-standing problem and the focus of an ongoing debate. Shlosman, Frank & Begelman (1989) argued that stellar-dynamical processes on scales of a few kpcs, and gas-dynamical processes on smaller scales, combine to drive the gas towards the centers and fuel the active galactic nuclei (AGNs). Sufficient evidence, observational and theoretical, supports the idea that nonaxisymmetries in the background gravitational potential, e.g., stellar bars, induce radial mass redistribution in disk galaxies (e.g., Simkin, Su & Schwarz 1980; Balick & Heckman 1982; Shlosman, Begelman & Frank 1990; Athanassoula 1994; Buta & Combes 1996). On the other hand, a number of optical surveys claimed no correlation between the large-scale morphology and the central activity (e.g., Moles, Márquez & Pérez 1995; Ho, Filippenko & Sargent 1997; Mulchaey & Regan 1997). The perennial question, therefore, to be addressed is *whether the AGN host galaxies differ morphologically from 'normal' (non-active) galaxies, and on what spatial scales.*

High-resolution near-infrared (NIR) observations are clearly advantageous in determining the mass distribution and hence detecting large-scale bars (McLeod & Rieke 1995; Mulchaey & Regan 1997; Peletier et al. 1999, hereafter Paper I). Knapen, Shlosman & Peletier (2000, Paper II) used sub-arcsec resolution imaging in three NIR bands (J, H, K) to study the complete CfA sample of Sy's and a *matched* control sample of normal galaxies using objective and stringent criteria for assigning bars. Here we look at a different aspect, and, instead of studying the frequency of bars in galaxies, investigate the bar axial ratios (i.e., bar ellipticities). This is done for *all* matching samples which are large enough and available in the literature. Bar parameters, such as strength, mass, and pattern speed, are very difficult to estimate from observations of stellar morphology alone. Even for the simplest models, bar strength depends on bar's quadrupole moment and on the radial distribution of axisymmetric mass in the disk, bulge and halo. The optical RC3 catalogue (de Vaucouleurs et al. 1991) recognizes three broad morphological classes, A, X, and B, i.e., nonbarred, intermediate barred and strongly barred. This RC3 classification, however, is subjective and has, to our knowledge, not been properly documented. We state that presently, it is not feasible to estimate the distribution of bar strengths proper in any statistically significant sample, but bar axial ratios can provide a reasonable alternative (Martin 1995). Here we develop this idea.

In this Letter we report a systematic difference in the distribution of the deprojected ellipticities of large-scale stellar bars between four samples of Sy and normal 'control' galaxies, of which three are independent. We describe the samples used, provide results of our analysis, and discuss their implications for understanding the AGN-host galaxy connection.

2. Observational Database

We use three independent samples of Sy's. NIR surface photometry is available for two of them, allowing us to apply our criteria for bar classification. Using a stringent criterion, we classified a galaxy barred, (Paper II) if *(i)* there is a significant rise in isophote ellipticity followed by a significant fall, $\Delta\epsilon_{\rm gal} > 0.1$, where $\epsilon_{\rm gal} \equiv 1 - b/a$ and a and b are semi-major and -minor isophote axes; *(ii)* the position angle of isophote major axis is constant within the bar range. The bar ellipticity was defined as $\epsilon_{\rm b} = 10\,{\rm max}(\epsilon_{\rm gal})$ (e.g., Martin 1995). A galaxy is also classified as barred if the major axis position angle shows a change of more than 75°, accompanied by an ellipticity above 0.1. Denoting large ellipticity (small axial ratio b/a) bars with *Strong* (i.e., 'thin' bars) and small ellipticity (large axial ratio) bars with *Weak* (i.e., 'fat' bars), we divided the deprojected range of bar ellipticities $\epsilon_{\rm b}$ into two groups, $\epsilon_{\rm b} < 4.5$ and ≥ 4.5. Our results do not depend critically on the boundary between these two groups (see below). Ellipticities $\epsilon_{\rm b} \leq 1$ were ignored and the galaxy was considered unbarred. For the samples based on the RC3 classification, 'S' and 'W' bar types were taken as the projected 'B' and 'X' types, respectively, but due to the uncertainty in relating the RC3 morphology to even the bar ellipticities, we do *not* base our conclusions on it. The following samples of Sy and matched normal (control) galaxies were used:

1. **KSP-RC3 Sample.** Paper II — CfA sample of Sy's (Huchra & Burg 1992) observed in NIR. Morphological classification from RC3. Galaxies were excluded when too small ($\log r_{H,19} < 0.8$, where $r_{H,19}$ is the isophotal radius in arcsec at $H = 19$ mag arcsec^{-2}), interacting (severely distorted or companion within $1'$), or highly in-

clined ($\epsilon_{\rm gal} > 0.5$). A synthetic control sample of normal galaxies chosen from the RC3 was closely matched to CfA Sy's in morphological type (including barred/un-barred), ellipticity and absolute magnitude (see Paper II for details about the technique used here).

2. **MRR-RC3 Sample.** Maiolino, Ruiz & Rieke (1995) — an optical Sy sample selected from the RSA Catalogue (Sandage & Tammann 1981). A synthetic control sample was constructed as for the KSP-RC3.

3. **MRK-RC3 Sample.** Mulchaey, Regan & Kundu (1997) — subset of Maiolino et al. (1995) observed in NIR. Morphological classification from the RC3, control sample as in KSP-RC3.

4. **HFS-RC3 Sample.** Ho et al. (1997) — very large optical sample of nearby AGNs, from Sy's to Liners and HII galaxies. We have taken all galaxies classified by Ho et al. as either Sy's or Transition objects (class T). Morphological classification from the RC3 and control sample as in KSP-RC3.

5. **KSP Samples.** Paper II — projected [KSP(p)] and deprojected [KSP(d)] bar ellipticities were determined on the basis of the photometric analysis of our NIR images of the CfA Sy and control samples.

6. **MRK Samples.** Mulchaey et al. (1997) — projected [MRK(p)] and deprojected [MRK(d)] bar ellipticities were determined by us from MRK's published ellipticities and position angle profiles for their Sy and control samples.

3. Statistical Results

Since we are only concerned here with the relative distribution of S vs. W-type bars in active and normal galaxies, we compare the frequency of S bars for Sy's, $f_{S(Sy)}$, namely,

$$f_{S(Sy)} = \frac{[S]}{[S+W]} \qquad (1)$$

with those in normal galaxies, $f_{S(Ctrl)}$. If the bar morphology in Sy's and normal galaxies is identical, both frequencies should be the same. However, Fig. 1 (see also Table 1) shows that in each individual sample studied there is a systematic deficiency of S-type bars in active galaxies, associated, however, with a relatively large uncertainty. The overall effect is at the 2σ level.

Table 1: Fractions of S- and W-type bars for different Sy and Control samples. Tabulated are the fractions of galaxies with S-type bars, and the number of galaxies used to obtain this number, $N_{\rm Sy}$ and $N_{\rm Ctrl}$. See text for description of the samples. BX in the last column indicates that the classification of the RC3 was used, while $\epsilon_{\rm b}$ means that our own ellipticity-criterion was used.

Sample	Sy [%]	$N_{\rm Sy}$	Ctrl [%]	$N_{\rm Ctrl}$	Crit
KSP-RC3	50±13	14	63.5±2	>2000	BX
MRR-RC3	54±7	54	63.4±2	>2000	BX
MRK-RC3	45±11	22	65.8±2	>2000	BX
HFS-RC3	40±7	52	61.0±2	>2000	BX
KSP(p)	70±10	23	76±12	17	$\epsilon_{\rm b}$
MRK(p)	42±10	24	56±12	18	$\epsilon_{\rm b}$
KSP(d)	48±12	23	59±12	17	$\epsilon_{\rm b}$
MRK(d)	33±10	24	50±12	18	$\epsilon_{\rm b}$

3.1. Testing the robustness of the result

A number of tests performed on the samples show that the result is a robust one, showing up across all the matching samples, but at the same time associated with relatively large uncertainties, since the available samples of Seyferts with near-IR surface photometry are still rather small. We have investigated several sources of systematic errors. First, because Sy's often have strong central point sources, the nuclear PSF would make the inner regions seem rounder than they are in reality, biasing the Sy bar shapes towards W-type bars, as compared to Control sample of normal galaxies. We have tested this hypothesis by searching the CfA Sy's which have a maximum in ellipticity (necessary condition for classification as a bar; Paper I) inside 5″. The effects of seeing outside this radius are negligible when the seeing itself is smaller than 1″ (e.g., Peletier et al. 1990). However, there is only one Sy galaxy, Mrk 270, which has max($\epsilon_{\rm b}$) within this range. No bar strength could be reliably determined for this object and it was not counted statistically, implying that the overall distribution of bar ellipticities is not affected by the Sy

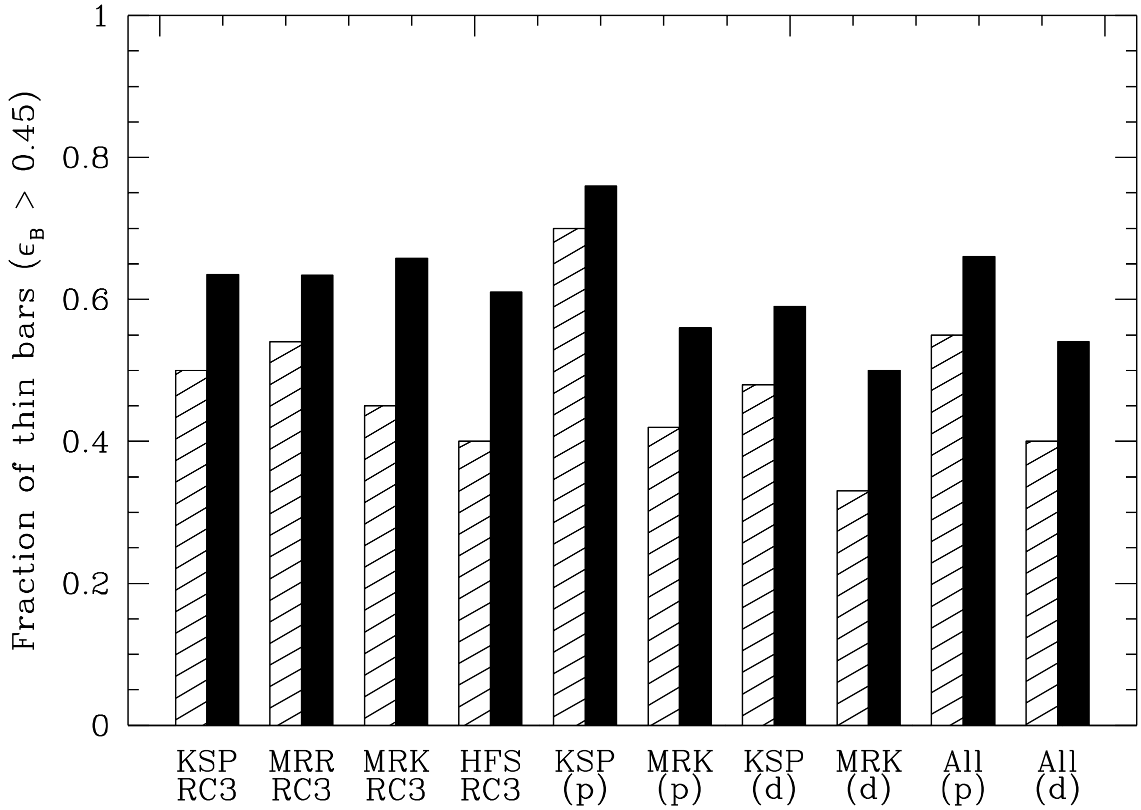

Fig. 1.— Fraction of S-type (high-ellipticity, thin, or 'strong') bars for barred Seyferts (dashed columns) in comparison with barred normal (control) galaxies (black columns), for all available samples. 'All' means KSP+MRK. The samples appear in the order of Section 2 and Table 1.

nuclei.

Second, because only relative numbers are used, this result does not change if projected or deprojected ϵ_b are invoked for statistics. Despite the fact that the RC3 control sample is at similar median redshift to our NIR samples, our analysis supports only a weak correlation between the subjective RC3 bar classification and the bar ellipticities, in agreement with Martin (1995, with more than 100 galaxies and RC3 classification) and Buta (1996, and private communications). The RC3 classifications were performed by eye, and it is not immediately clear what exact criteria have been used for classifying a galaxy as B or X. Out of the 40 galaxies of the KSP and control samples which were classified as barred by us, 16 appear unbarred (neither B nor X) in the RC3 (Paper II). Possible reasons for this difference include the presence of dust, the small size of the bar, or the inferior resolution in the RC3. The density contrast between the bar and the surrounding disk provides an additional complication. When the contrast is large, it is much easier to classify a galaxy as barred. Neither Martin's sample nor the KSP sample show much of a correlation between ϵ_b and B or X. The results based on RC3 classifications should be, therefore, interpreted with the necessary caution. The strength of our analysis is in that we use both ϵ_b and the RC3 classification to subdivide the objects into S and W-type bars, and both approaches supplement each other in Fig. 1 and Table 1.

Third, we tested the sensitivity of our results to the assumed boundary between S and W-type bars. This was achieved by moving this boundary between 0.35 and 0.55 (Table 2). Moving it even more would not

Table 2: The fraction of Seyferts with thin (S) bars for various values of the ϵ-boundary dividing W and S-type bars. 'All' means KSP+MRK.

ϵ-boundary	KSP Sey.	Proj. Ctrl.	KSP Sey.	Depr. Ctrl.	MRK Sey.	Proj. Ctrl.	MRK Sey.	Depr. Ctrl.	All Sey.	Proj. Ctrl.	All Sey.	Depr. Ctrl.
3.5	0.83	0.88	0.65	0.82	0.88	0.67	0.54	0.61	0.85	0.77	0.60	0.71
$\pm$	0.08	0.08	0.10	0.09	0.07	0.11	0.10	0.12	0.05	0.07	0.07	0.08
4.0	0.83	0.88	0.52	0.77	0.63	0.67	0.50	0.56	0.72	0.77	0.51	0.66
$\pm$	0.08	0.08	0.10	0.10	0.10	0.11	0.10	0.12	0.07	0.07	0.07	0.08
4.5	0.70	0.77	0.48	0.59	0.42	0.56	0.33	0.50	0.55	0.66	0.40	0.54
$\pm$	0.10	0.10	0.10	0.12	0.10	0.12	0.10	0.12	0.07	0.08	0.07	0.08
5.0	0.70	0.77	0.44	0.53	0.38	0.44	0.17	0.50	0.53	0.60	0.30	0.51
$\pm$	0.10	0.10	0.10	0.12	0.10	0.12	0.08	0.12	0.07	0.08	0.07	0.08
5.5	0.44	0.47	0.30	0.29	0.29	0.33	0.08	0.28	0.36	0.40	0.19	0.29
$\pm$	0.10	0.12	0.10	0.11	0.09	0.11	0.06	0.11	0.07	0.08	0.06	0.08

leave enough galaxies in either the weak or the strong bins. The fraction of S or W bars does not depend critically on the exact position of the boundary. For each sample individually the error is rather large, but for all the samples the frequency of S bars in Seyferts lies below that of the control sample. To show the significance of this result, we have constructed a larger sample by taking together all Seyferts of MRK and KSP, and comparing them with a Control sample consisting of both control samples combined (the last two columns of Table 2 and Fig. 2).

Fourth, we have performed Kolmogorov-Smyrnov tests to check whether Seyfert and Control samples can be seen as drawn from the same intrinsic distribution. For the deprojected KSP sample the probability that this is in fact the case is 53%. For the deprojected MRK sample we find 11%, while for the projected samples the probability is 72% and 54%, respectively. These numbers show that this test is inconclusive. It does not show that it is likely that the fractions of S and W-type bars are different in Seyferts from those in non-Seyferts, although it can not exclude this possibility.

In any case, independent of the exact method by which the bar type, S or W, was determined (i.e., based on RC3 classification, projected or deprojected bar ellipticities), the frequency of S bars in Seyferts is systematically lower than in normal galaxies. We conclude that the result that Sy's have more W-type ('fat') bars than S-type ('thin') bars in normal galaxies is robust, and that it is found for a variety of samples with bars measured in a number of ways.

4. Discussion

All samples used in the previous section provide a coherent picture of bar ellipticity distribution in barred Sy hosts and matching control samples of normal barred galaxies. The most intriguing and important result is the apparent deficiency of stellar bars with large ellipticities (i.e., large $\epsilon_{\rm b}$) in Sy's, compared to those found in their non-active counterparts. Although this effect is at the level of $\sim 2\sigma$, due to small number statistics, it is consistent across all the Sy and matching control samples.

There are two possible explanations for the observed phenomena within the framework of galaxy evolution both of which are dependent on the cold gas component in the disk. First, numerical simulations of pure stellar disks have shown that the bar instability becomes milder, i.e., produces a bar with smaller ellipticities, if the disk is hotter initially, prior to instability (Athanassoula 1983). This can be understood as weaker swing amplification in disks with larger velocity dispersion (Toomre 1981). An additional caveat is that the presence of a cold and clumpy gas component in the disk provides a heating source for stars and acts to weaken *all* dynamical instabilities, including the bar instability (Shlosman & Noguchi 1993) and the vertical bending of the bar (Berentzen et al. 1998). Gas gravity is crucial here and even reasonable amounts of cold gas are suffi-

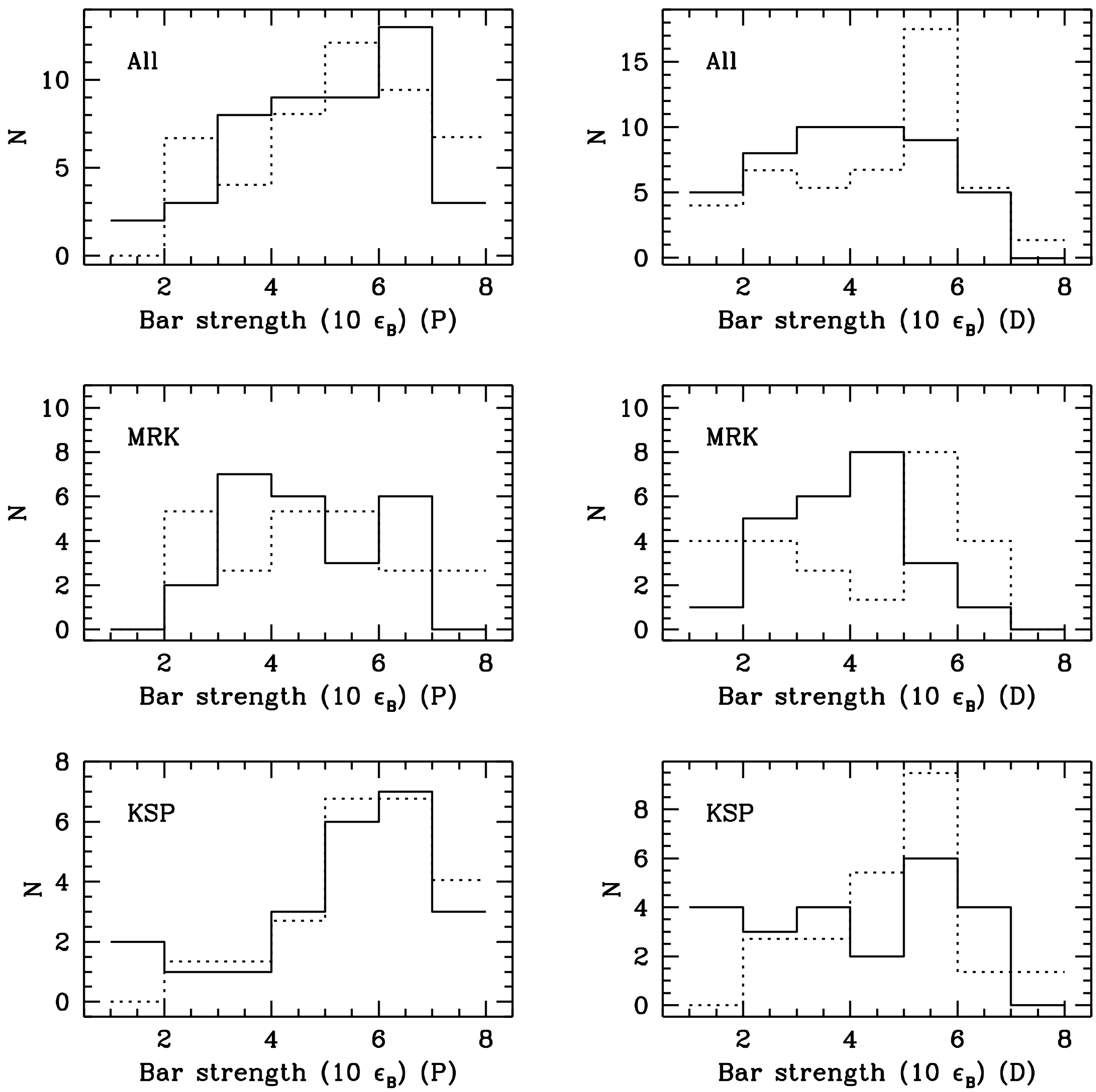

Fig. 2.— Distribution of bar ellipticities in projected and deprojected KSP, MRK and 'All' (see the text) samples for Sy (solid lines) and Control (dashed) galaxies. The Control distributions were scaled to Sy ones for comparison.

cient to suppress the instabilities altogether. If indeed Sy disks have a larger fraction of cold gas than normal galaxies (e.g., Hunt et al. 1999), which may also be more clumpy, this trend should be explored more fully. The resulting difference(s) between Sy and normal disks will be long-lasting because the stellar component, once heated up, will not be able to cool down easily, as the stellar 'fluid' is non-dissipative.

Our understanding of the evolution of barred galaxies points to an alternative and possibly more elegant explanation for the observed difference in bar properties between active and normal galaxies. Numerical simulations of bars revealed their weakening with time in response to a growing mass concentration in the galactic centers (Hasan & Norman 1990; Friedli & Benz 1993; Hasan, Pfenniger & Norman 1993; Berentzen et al. 1998). The radial gas inflow towards the central kpc and further inwards is the prime suspect. All or part of this gas can contribute to the growth of galactic bulges, nuclear rings, disks and bars, and ultimately to central black holes (BHs) by dissolution of the main family of periodic orbits supporting the large-scale stellar bars. These so-called x_1 orbits (e.g., Sellwood & Wilkinson 1993) are replaced by stochastic orbits when the mass of the central BH exceeds $\sim 1\%$ of the total mass. Heller & Shlosman (1996) also found that nuclear rings with masses greater than a few $\times 10^9$ $M_\odot$ lead to x_1 orbit dissolution exterior to the ring, leaving smaller bar remnants escaping detection inside the central kpc.

In view of the fact that the supermassive BHs appear to be ubiquitous in normal galaxies (Kormendy & Richstone 1995) and not only in Sy nuclei, it seems relevant to ask why the Sy hosts are affected more by the bar dissolution processes than normal galaxies. A resolution of this paradox can lie in that the BHs in Sy's are more massive than in their non-active counterparts, but only statistically. If indeed supermassive BHs play a role in the bar dissolution, we anticipate that their instantaneous mass distributions in Sy's and normal hosts peak at different values, but have a large overlap. Moreover, it is plausible that ground-based observations based on stellar-dynamical considerations overestimate the BH masses in normal galaxies due to insufficient spatial resolution. These mass estimates may be lowered by upcoming HST observations.

In summary, we have analyzed all available reasonably-sized samples of Sy host galaxies and independent control samples of normal galaxies carefully matched in type, disk ellipticity, absolute magnitude, and, to some extent, in redshift. We find that samples of active galaxies are systematically deficient in high-ellipticity 'thin' stellar bars compared to normal galaxies. The associated uncertainty is quite large and the overall effect is at the 2σ level. We discuss the corollaries of this effect. The acceptable alternatives point towards the cold and clumpy gas component in the disk as being responsible for the observed effect. Our result provides an indication that Sy host galaxies differ systematically on scales of a few kpc from their normal counterparts, and that the gas component may be responsible for this.

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